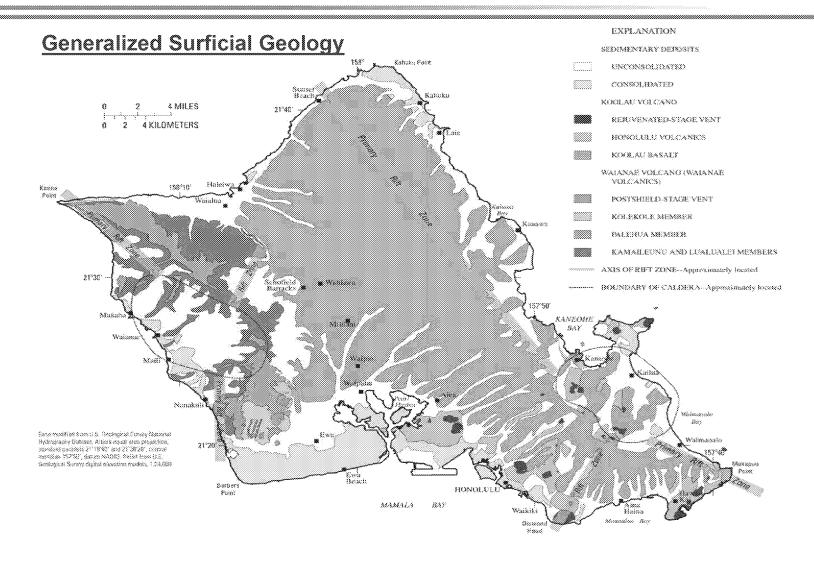
Site Geology and Hydrogeology: Regional Geology





Site Geology and Hydrogeology: **Regional Geology**



Waianae and Koolau volcanic-rock aquifers

EXPLANATION

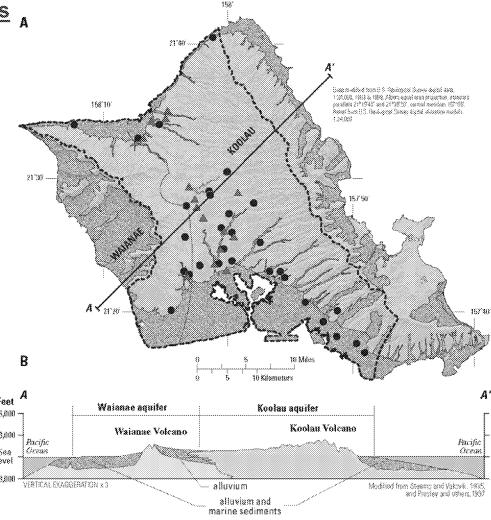
MAJOR VOLCANIC-ROCK AQUIFERS, UNCONFINED Koolau aquifer

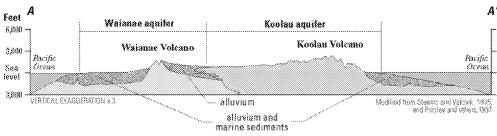
Waianae aguifer

SEDIMENT OVERLYING AND CONFINING MAJOR VOLCANIC-ROCK AQUIFER

LINE OF SECTION NAWOA GROUND-WATER STUDY AREA PUBLIC-SÚPPLY WELL

MONITORING WELL





Site Geology and Hydrogeology: Regional Geology



- Four major geomorphic provinces define the Island of Oahu: two volcanic mountain ranges (Waianae and Koʻolau), the Schofield Plateau, and the Ewa coastal plain (Stearns and Vaksvik, 1935).
- The Ko'olau Volcanic Series is made up almost entirely of tholeiitic basalts and olivine basalts.
- The southeastern third of Koʻolau volcano's remnant shield experienced a rejuvenation stage of volcanism. Most rejuvenation stage volcanoes lie south of the erosional valleys carved out of the Koʻolau shield and are interbedded with alluvial and marine sediments. These rejuvenation stage vents and associated flows and ash deposits comprise the Honolulu Volcanic Series.



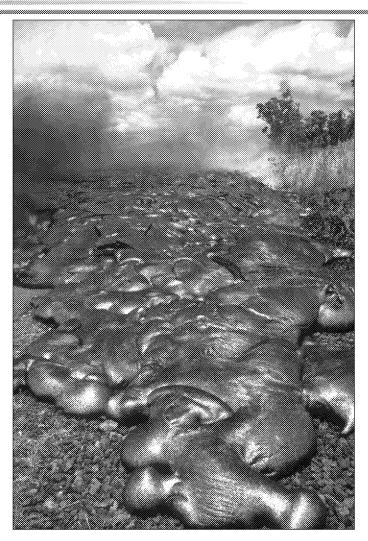
- Volcanic formations in Hawaii can be divided into four groups, all of which may be present at Red Hill:
 - 1. Lava flows (extrusive)
 - 2. Dikes and sills (intrusive)
 - 3. Pyroclastic deposits (extrusive, e.g. volcanic tuff)
 - 4. Saprolite and weathered (soil) horizons
- These groups of rocks have markedly different physical and hydraulic properties
- Interbedded flows often result in highly heterogeneous formations



Types of Hawaiian lava flows:

1. Pahoehoe

- Less viscous flows; vesicular, smooth, ropy
- Smoothly undulating surface;
 numerous elongate voids
 - Voids can form in the horizontal, longitudinal direction, creating preferential pathways
- Formed as fluid, relatively rapidly flowing basaltic lavas that tend to spread out
- Typically thin flows with voids of various sizes; cracked and collapsed in places
- Lava tubes are associated with pahoehoe lava flows





Types of Hawaiian lava flows:

2. A'a

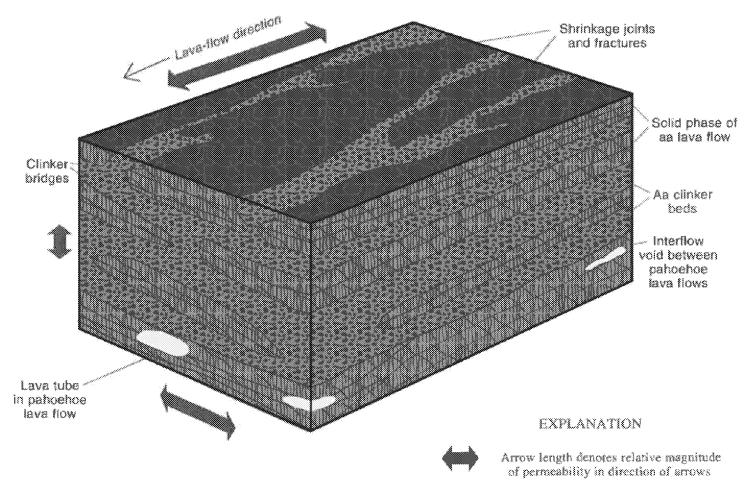
- Solid, massive cores with top and bottom clinker zones
- Clinker:
 - · Like a coarse, well-sorted gravel
 - Layered sequences of flows can result in widespread beds with high horizontal permeability
- The smaller effective porosity of massive a'a cores can result in extremely low vertical permeability
 - The principal vertical permeability of an a'a core is imparted by wide regularly spaced cooling joints, which are typically low permeability





GEOHYDROLOGY OF THE WATER-BEARING DEPOSITS

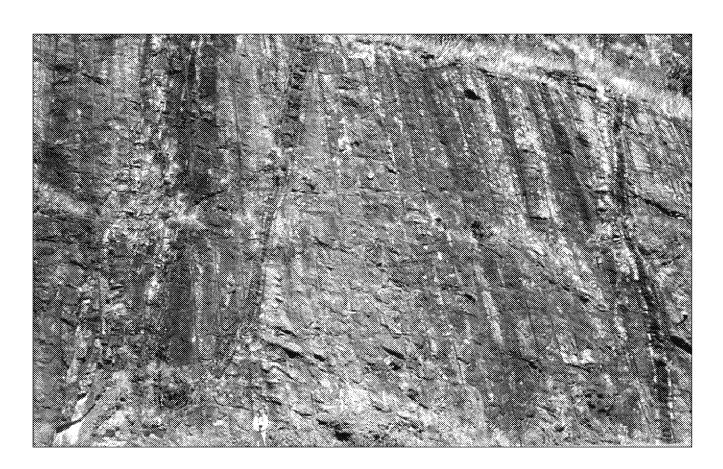
Successive interbedded pahoehoe and massive a'a often create highly irregular formations with various fractures and voids, intermixed with widespread areas of high horizontal permeability





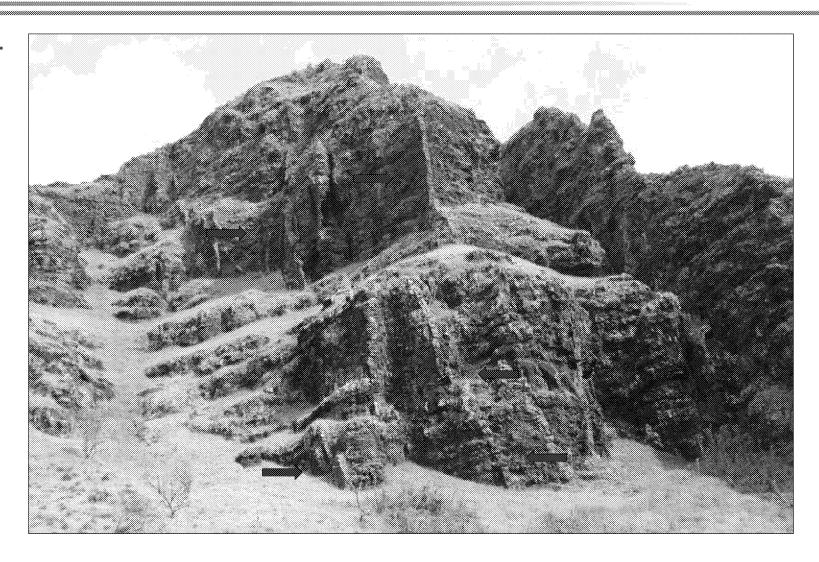
Dikes:

- Thin, near-vertical sheets of massive, intrusive rock
- Typically only fractures contribute to porosity and permeability
- Often no more than several feet thick, but can extend vertically thousands of feet and laterally several miles
- Where dikes intrude lava flows, they inhibit ground-water flow principally in the direction normal to the plane of the dike





Dikes:





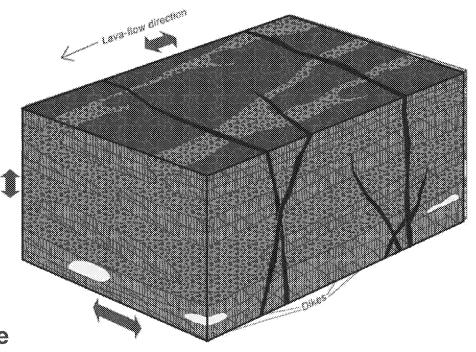
Dike Complexes:

- Areas with numerous dikes that intersect at various angles
- Form small compartments
- Lower overall rock porosity and permeability¹

Marginal Dike zones:

- Areas where vertical dikes are subparallel and widely scattered
- Can impound water within large compartments of more permeable lavas
- Tend to channel ground-water flow parallel to the general trend of the dikes²

 1 Takasaki and Mink. 1985



² Hirashima, 1962; Takasaki, 1971



Pyroclastic Deposits:

- Pyroclastic (airfall) granular deposits include ash, cinder, spatter, and larger blocks
- Porosity and permeability are similar to that of granular sediments with similar grain size and degree of sorting
- Fine-grained ash is less permeable than coarse pyroclastic deposits such as cinder and spatter
- Permeability of ash may be reduced further by weathering or by compaction to tuff; weathered ash beds can act as thin confining units within lava sequences





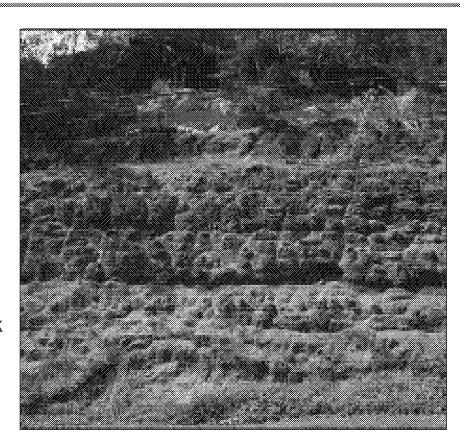
 Weathering between flow events ("hiatuses") can form weathered soil horizons with lower permeability.





Saprolite:

- Weathered material; retains textural features of parent rock
- · Can be 300 feet thick
- Percolating water beneath stream channels in valleys often significantly increases the depth of weathering
- Rocks with a high proportion of pore space and surface area, such as ash, cinder, and a'a clinker, are weathered preferentially; weathering of massive rock proceeds more slowly
- Principal permeability in massive a'a is along vertical cooling joints; slight weathering and swelling can seal these joints, resulting in a layer of low vertical permeability

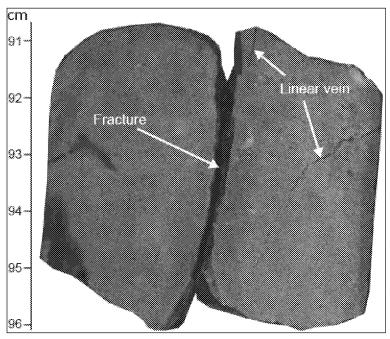


Site Geology and Hydrogeology: Porosity in Volcanic Rocks



 Fracture joints, cracks, and bedding plane separations can form during emplacement or from weathering





Site Geology and Hydrogeology: Porosity in Volcanic Rocks



- Intergranular fragmental rocks (like clean course gravel):
 - Scoria/Cinder highly vesicular lava fragments that are explosively ejected from a vent

Rubble and clinkers in an a'a flow





Site Geology and Hydrogeology: Porosity in Volcanic Rocks



- Conduits/large openings (like limestone solution conduits):
 - Lava tubes naturally formed tunnel in a lava flow, created by crusting of lava over the main lava channel, followed by drainage of lava, follows direction of flow
 - Interflow (typically horizontal)
 voids formed by cooling and expanding lava during emplacement



Site Geology and Hydrogeology: Permeability in Volcanic Rock Formation



The permeability of Hawaiian volcanic rock formation is highly variable depending on:

- Vesicle fraction
- Type of emplacement
 - Extrusive (lava flows)
 - Intrusive (dikes/sills)
 - Explosive/airfall (pyroclastics)
- Presence of interflow zones and voids
- Reduction in permeability by weathering

Site Geology and Hydrogeology: Permeability in Volcanic Rock Formation

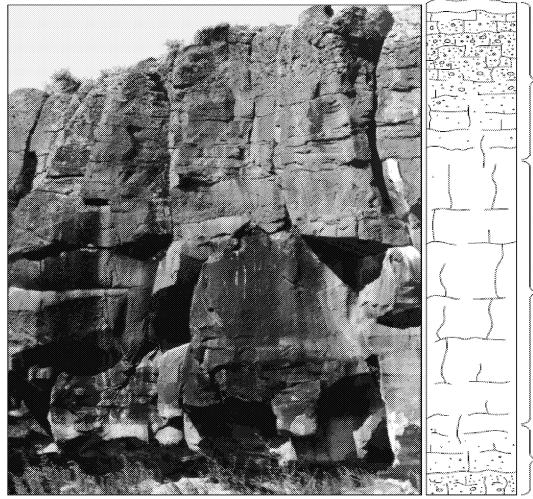


- High permeability (often horizontal)
 - Thin pahoehoe flows (large number of interflow zones)
 - Vesiculated lava flow tops
 - Rubbly a'a flow base and top (a'a clinker zones)
 - Highly fractured rocks
- Low permeability (potential confining layers) (often vertical)
 - Massive a'a flows
 - Massive unweathered intrusive rocks (dikes/sills)
 - Ash beds
 - Weathered rocks (saprolite)/soil horizons
- Net result:
 - Highly complex & variable rock type & fabric, frequently resulting in highly variable permeability and unpredictable flow patterns
 - Vertical permeability often orders of magnitude lower than horizontal
 - Horizontal permeability significantly higher in direction of flow

Site Geology and Hydrogeology: Permeability in Volcanic Rock Formation



Massive a'a flow displays highly variable permeability



Modified from Whitehead, 1992

Flow top vesicular, scoriaceous and broken; substantial permeability

Flow center dense, few vesicles, most fractures are vertical; minimal permeability

Flow bottom– vesicular and broken; substantial permeability

Site Geology and Hydrogeology: Porosity and Permeability Variability at the Site



• RHMW07 (surface elevation = 216.53 ft. msl)

Core interval 40 – 50 ft. bgs (166.5 – 176.5 ft. msl)



Site Geology and Hydrogeology: Porosity and Permeability Variability at the Site



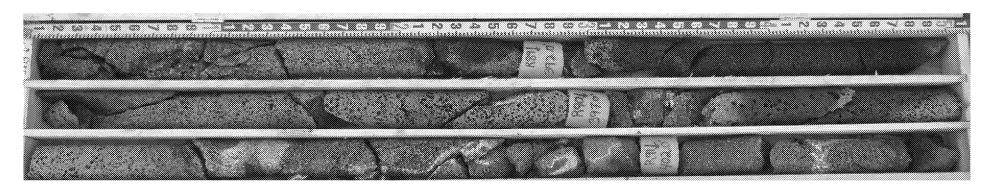
- RHMW07 (surface elevation = 216.53 ft. msl)
 - Core interval: 160 170 ft bgs (46.5 56.5 ft. msl)



Site Geology and Hydrogeology: Porosity and Permeability Variability at the Site



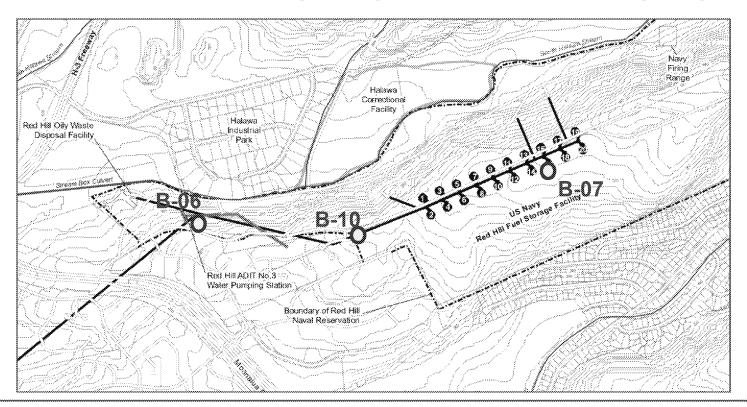
Core interval 399.4 – 404.4 ft. bgs (135.6 – 141.6 ft. msl)



Pahoehoe lava (medium to high permeability due to interflow zones and fracture)



- Previous Red Hill investigations
 - Boring logs and rock cores from a previous site investigation conducted in 2012 and 2013
 - 10 surface borings along tunnel alignment mauka to makai starting atop Red Hill
 - 2 obs in B-07 at 102' msl (slight fuel gas odor) and 92' msl (strong fuel gas odor)





- Geologic CSM of the Red Hill vadose zone
 - Overall, the Red Hill vadose zone is highly heterogeneous and anisotropic
 - Interbedded flows of different types of lava likely flowed from different directions at different times, may have been weathered between flows (potentially forming weathered horizons and soil), resulting in the presence of sizable voids and relatively impermeable regions or zones in unpredictable locations
 - Formation of lava tubes, dikes, sills, weathering and other factors likely resulted in the formation of sizable voids that are not interconnected and relatively impermeable in the vertical direction



- The Geologic CSM of the Red Hill Vadose Zone:
 - May explain no measurable LNAPL in monitoring wells
 - Argues for limiting drilling near the tank farm; to avoid creating pathways through confining layers to the groundwater
 - Would make it very difficult to locate NAPL via drilling
 - Explains the difficulties and dangers that active remediation or removal of NAPL would entail
 - Suggests the formation is relatively oxygen-rich, promoting natural attenuation of petroleum products
 - Suggests that vadose zone numerical flow modeling would not produce meaningful, reliable, or reproducible results
 - Models developed for porous media or for fractured (mainland) bedrock would not be expected to reflect Hawaiian geology with any degree of accuracy

Site Geology and Hydrogeology: Hydrogeology



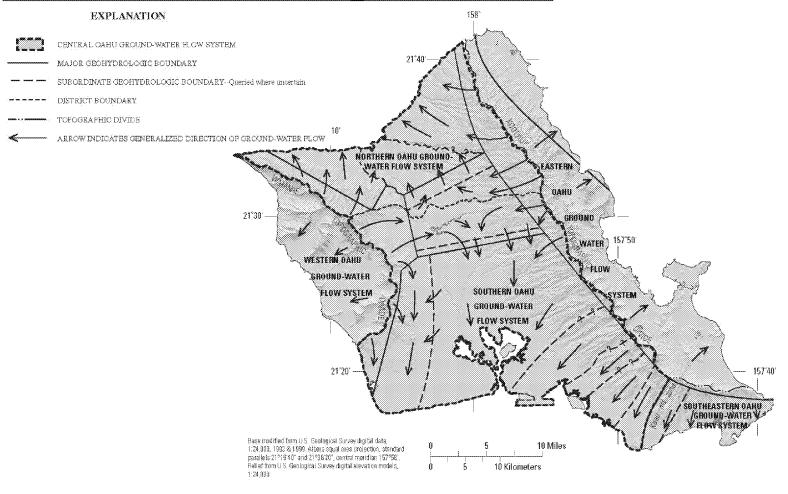
Hydrogeology

- Principal aquifer is comprised of high horizontal permeability (high K) zones, hydraulically interconnected at the site scale
- Low permeability zones of unfractured basalt and dikes form barriers to groundwater flow
- Valley fill sediments are fine grained, forming (low K) flow barriers
- Caprock of intermediate permeability occurs west of site

Site Geology and Hydrogeology: Hydrogeology



Groundwater Flow Systems, Oahu, Hawaii (Hunt 1996)



Site Geology and Hydrogeology: Hydrogeology



